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NANO-DISKS AS λ -SIZE ANTENNAS

ABHISHEK TIWARI, NEETI DUGAYA & MANOJ PITALE

M. Tech. Scholar GGITM Bhopal, Assistant Professor SIRTS Bhopal, Engineering Graduate RGTU, India

ABSTRACT

Cathodoluminescence imaging and spectroscopy allows mapping of different modes of plasmonic Nano-disks that are comparable in different size. Investigations using panchromatic images as well as spectral analysis suggests that small disks are good candidates for single mode resonances; however, as the disk size increases more modes are observed. Monochromatic images of these modes showed they are strongly dependent on their size as well as the location of the excitation source. The strong dependence of geometry is characterized using three disks with circular, octagonal and square shapes. When a circular disk is modified to octagonal, splitting of the peak for center excited mode was observed. The perturbation created at the edges results in two separate whispering gallery-type modes that have different SPP path lengths showing field maxima at corners and edges. Therefore, imperfections resulting from fabrication (edge roughness, roundness, etc.) of plasmonic devices can have important implications on next generation plasmonic applications (e.g., lasing cavities) and should be included during characterization. In this paper the effect of different disc geometries on mode splitting has been discussed along with plasmonic modes of Nano-disk.

GENERAL TERMS

Spectroscopy, Disc geometry, Nano-disc

KEYWORDS: Plasmonic Devices, Nanocavities, Cathodoluminescence

INTRODUCTION

Most of the efforts in previous chapters have been devoted to studies involving sub wave length antennas with characteristic dimensions close to 100 nm. The nanostructures probed here are comparable to their resonance wavelengths with typical dimensions ranging between 50 nm to all the way up to 1 µm. These plasmonicnanocavities with very small mode volumes offer thresholdless laser operation by combining spontaneous emission with the lasing mode [1-3, 4-7]. The ultra small optical devices are of interest because of their low power consumption and possibility of large scale integration into current electronic devices and future all-optical systems [8]. They are important candidates for studying exciton-photon interaction and cavity quantum electrodynamics [8]. Nano-cavities can be potentially used as single photon sources that are important for quantum computing and highly secure optical communication; however, these sources require high efficiency, low multiphoton probability, and quantum indistinguish ability [8-9]. Conventional microdisk lasers rely on total internal reflection at the walls for the whispering gallery modes with very high quality factor [9]. However, for plasmonicnano-disk resonators with very small mode volume, the lowest-order modes are TM (1, 1) modes with enhanced fields at the edges [10]. As the size of the disk increases, more azimuthal and radial modes can be supported. Additionally, it has also been shown that degenerate whispering gallery (WG) modes dominate for larger disks [11], and can 61 show significant mode splitting, e.g., due to structural imperfections [12]. The nature of these WG modes and the role of disk geometry on mode profile, field enhancement and mode splitting are not well understood. In the

current studies, electron-beam excitation is used to probe some of these modes on gold and silver Nano-disks. By fixing the beam at specific locations of the Nano-disk, individual modes can be selectively excited. The samples in these studies were coated with a 2 nm thin Al2O3 layer using atomic layer deposition (ALD) to reduce the damage from high velocity electrons. Gold was found to be less susceptible to such damage, and studies requiring repetitive scans on the same disks were carried out on Au samples. This helped avoid any effects such damage might have on the characterization.

Plasmonic Modes of Nano-Disks

Parametric studies of Ag Nano-disks show they can sustain several modes depending on their size. Panchromatic images of 50 nm thick Ag disks shown in Figure 1 (a) reveal these modes. For smaller disks up to 150 nm diameter, single TM (1, 1) modes with high luminescence from the edges are observed. As the size of the disk increases, more modes start to appear with predominantly bright center. By fixing the electron beam at the center of disks, these Bessel modes can be selectively excited. Spectra shown in Figure 1 (b) show several peaks from this excitation. Beside the bulk mode of silver near 330 nm [13], a strong peak is observed that red-shifts with increasing disk diameter as plotted in Figure 1 (c). With larger disks, higher modes can also be excited resulting in more peaks but fewer counts per mode. This behavior is uniformly observed, more or 62 less, for all the three geometries studied here; however some important distinctions will be reported in the next section. Therefore, metal Nano-cavities designed for coupling spontaneous emission into lasing modes should be designed by considering their size and respective mode profiles for maximum field enhancement in the active medium.

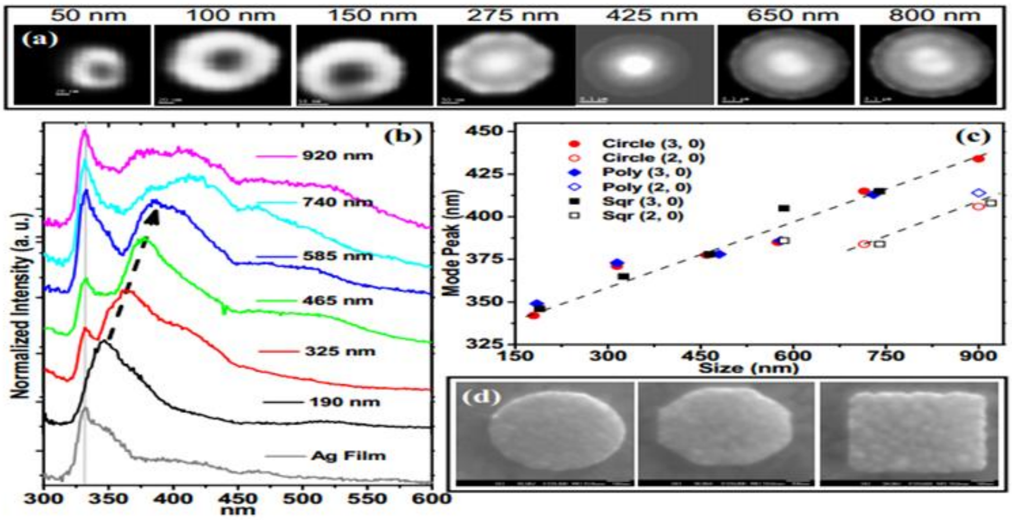

Figure 1: Parametric study of Nano-disk modes using cathodoluminescence imaging and spectroscopy. (a) Panchromatic images of 50 nm thick Ag disks of various sizes showing different modes supported on them. (b) Spectra taken by fixing the electron beam at the center of similar Ag disks; (c) plots of the dominant mode against disk diameter for three different geometries; (d) representative SEM images of three geometries considered here—circular, polygonal and square. 300 350 400 450 500 550 600 920 nm 740 nm Normalized Intensity (a. u.) 585 nm 465 nm 325 nm 190 nm nm Ag Film 150 300 450 600 750 900 325 350 375 400 425 450 Mode Peak (nm) Size (nm) Circle (3, 0) Circle (2, 0) Poly (3, 0) Poly (2, 0) Sqr (3, 0) Sqr (2, 0) (b) (c) (d) 50 nm 100 nm 275 nm 150 nm 425 nm 650 nm 800 n m (a) 63

Figure 2: shows spectral analysis and corresponding images of various modes of a 900 nm Au disk. The spectra were taken along a line joining the center of the disk to one of the corners as shown by the numbers in the SEM image. Panchromatic images of the same disk show high luminescent corners suggesting a collage of modes with maxima at the corners and edges. The spectra show several peaks corresponding to the different modes the fixed beam is able to excite.

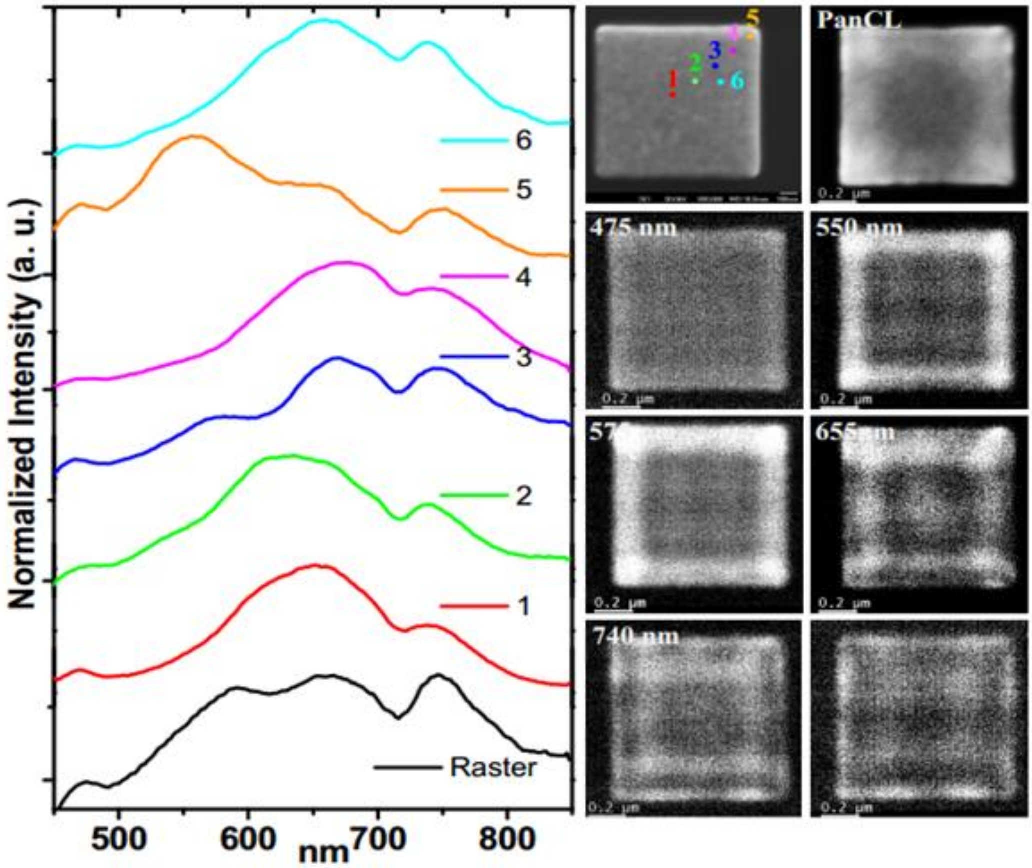

Figure 2: Spectral and imaging analysis of 50 nm thick Au Nano-disk with 900 nm edge. The spectra collected at different positions of the disk (as numbered in SEM image) show peaks corresponding to different modes. Some of these modes are captured in the monochromatic images as shown on the right.

For smaller wavelengths, Au is very lossy [14, 1, 15, 16] and barely any charge oscillations in the monochromatic images can be observed. However, with increasing wavelengths, oscillations of the surface Plasmon wave on the disk result in interference patterns in both in-plane horizontal and vertical directions [17-18]. These maxima and minima are captured as centers of high and low luminescence, respectively. Note that only modes that are multiples of half-wavelengths can be sustained. This allows calculation of SPP wavelengths for the various modes observed here; e.g., the three half wavelengths observed at 655 nm correspond to an SPP wavelength of 640 nm while the four half-wavelengths at 550 nm correspond to 510 nm. The corresponding wavelengths calculated from dispersion relation of 50 nm thick Au film are at 620 nm and 504 nm, respectively.

Effect of Disk Geometry on Mode Splitting

In this section, the effect of geometry on plasmonic modes of a silver Nano-disk is investigated. By positioning the electron-beam at specific locations of a Nano-disk, completely different modes can be excited that are strongly

dependent on disk-geometry. Panchromatic imaging of a circular disk shows strong luminescence at the center; however, as the disk "circularity" is modified from circular to octagonal, new modes at the periphery are observed. Investigations of octagonal disks reveal the appearance of whispering gallery-type modes attributed to splitting of degeneracy. For a square disk, a more uniform luminescence across the disk is observed suggesting weak coupling of the electron beam. 65 50 nm thick Ag disks with diameter of 425 nm were fabricated on 85 nm thick SiO2 layer deposited on Si substrate as shown in Figure3. To avoid any damage to the Ag nanostructure, no RIE or wet etching was attempted as reported in the previous Chapter. This size was chosen because smaller disks prominently show TM (1, 1) modes [10] with fields concentrated on the edges, making the current observations much more difficult to separate; for larger disks, more modes start to appear, resulting in a much more complicated system. Detailed analysis of modes on this disk shows that a beam focused at the center of the disk excites whispering gallery type modes which are strongly dependent on the disk geometry.

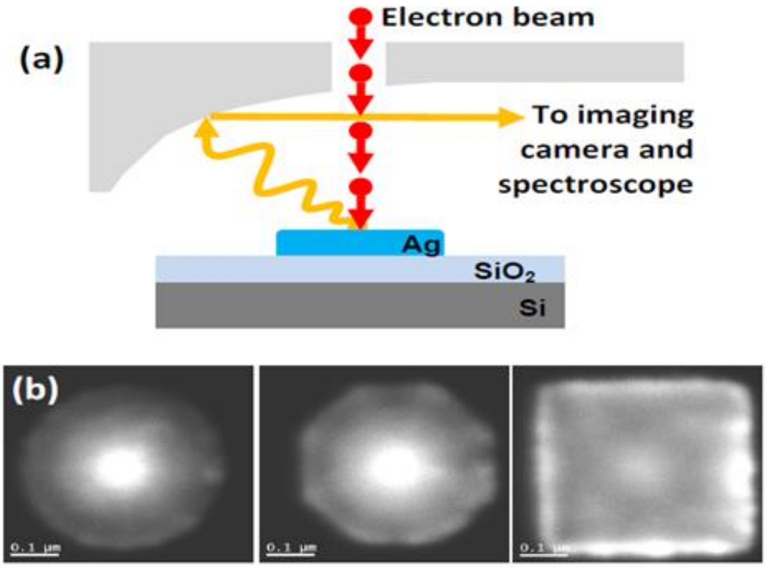

Figure 3: (a) Schematic of the sample design and cathodoluminescence setup. (b) Panchromatic images of the Nano-disks compared for studying role of geometry on disk modes. The circular disk shows a prominently luminescent center while the octagonal disk also shows enhanced periphery suggesting appearance of new modes as the "circularity" of the disk is modified. The square disk has a weakly luminescent center but more uniform emission.

Figure 3 (b) shows panchromatic CL images of three disks with characteristic dimensions of 425 nm but varying "circularity"—from fully circular to a square disk. The images reveal a strong emission from the center suggesting the predominant modes to be Bessel modes of the first kind which have their maxima at center and have been studied earlier in plasmonic Nano-disks [10] and micro-disk lasers [9]. The images also show that intensity at the center is strongly dependent on the geometry and lower contrast is observed as the disk changes from circular to square. While a fully circular disk shows a very strong luminescent center suggesting a predominantly single mode excitation, the square disk suggests either weak coupling with electron beam or excitation of several modes with comparable efficiency, making the whole disk uniformly luminescent. Interestingly, the octagonal disk shows increased luminescence at the periphery suggesting emergence of additional modes as imperfections are added to the periphery. In that sense, the octagonal disk appears to be a good candidate to understand how geometry affects the coupling of electron beam with a plasmonic Nano-disk. This can help in understanding and designing, e.g., single mode Nano-lasers with desired side-mode

suppression ratio by preferably coupling light into the lasing mode. For the purpose of understanding how change in "circularity" affects luminescence observed in panchromatic images, detailed studies of the octagonal disk were carried out. Because electron-beam allows localized excitation of the disks—in a way analogous to hitting an acoustic drum at different locations and creating unique sounds—it is worthwhile to focus the beam at several positions and investigate corresponding modes.

Figure 4 (a) shows spectra taken by positioning the beam at different locations on the disk. When the beam is fixed at the edge or corner of disk, a 67 strong peak at the 345 nm is observed. This peak corresponds to the surface Plasmonpolariton (SPP) peak of Ag [13], and therefore suggests generation of travelling SPPs at the periphery that result in whispering gallery modes on the disk. The spectrum taken by fixing the beam at the center shows two peaks at 370 nm and 420 nm. Additionally, a beam localized at half radius from center to edge shows a predominant peak at 370 nm and a relatively weak peak at 420 nm. All the spectra also show a bulk Plasmon peak of silver at 328 nm [13] and another peak of varying strength at 455 nm from the SiO2 substrate [19]. FDTD simulations carried out using a line charge of dipoles show excellent agreement with the observed peaks.

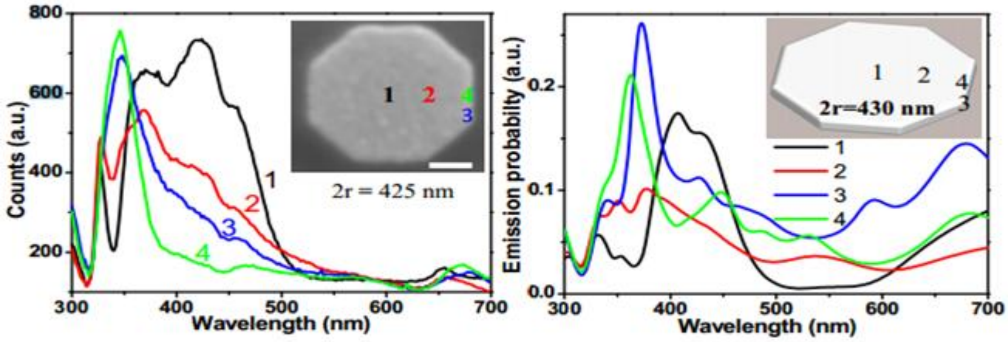

Figure 4: (a) Cathodoluminescence spectra taken by positioning the electron-beam at different locations on an octagonal disk of corner-to-corner diameter of 425 nm. The numbers indicate position of the beam for different spectra. Center excitation shows two peaks at 370 nm and 420 nm while excitation at half-radius predominantly excites 370 nm mode. The 455 nm peak is from SiO2 substrate; (b) FDTD simulation confirming the experimental observation.

Because an increased luminescence is observed at the periphery when the disk is modified from circular to octagonal, any changes in the geometry should accompany excitation of new modes at the periphery, either by exciting higher Bessel modes—which 4 1 2 2r=430 nm 3 300 400 500 600 700 0.0 0.1 0.2 1 2 3 4 Emission probabilty (a. u.) Wavelength (nm) 300 400 500 600 700 200 400 600 800 Counts (a.u.) Wavelength (nm) 1 2 3 4 1 2 4 3 2r = 425 nm 68 have multiple nodes away from the center—or completely different kind of modes that localize at the periphery. The first case is unlikely since the central node of higher Bessel functions should be more tightly focused to accommodate additional nodes while we observe similar (or slightly diffused) central node. To verify the second possibility, spectra taken by fixing the beam were compared, as was done for the octagonal case above. When the beam is fixed at the periphery, travelling surface plasmons of the whispering gallery modes should be expected. Their peak should remain the same although the luminescence might change depending on how efficiently they are excited. Interestingly, a comparison of spectra taken by fixing the beam at the center of the three disks showed very different behavior. For the circular and square disks, only one peak is observed instead of the two non-degenerate peaks observed for the octagonal disk. Simulations of

this observation for the three disks by fixing the electron beam in the center show splitting of the degenerate modes as the "circularity" is gradually changed (Figure 5 (b)). More interestingly, the field profiles for the two modes suggest two whispering gallery (WG) type modes with different field maxima (Figure 5 (c)). For the low energy mode, the field is concentrated on corners of the disk while for the higher energy mode, this field maxima lies on edges. One approach to understand the splitting is by comparing the total surface area of the two modes. When the field maxima spots are connected using a polyline, the area within the polygon of high energy edge mode is found to be smaller than the low energy mode. Therefore, the change in periphery has resulted in excitation of two different Bessel functions of different sizes. For the square case, several such modes can be sustained making the disk much more luminescent as is confirmed by the broad simulated peak. However, the single weak peak in the 69 experiments suggests one of these modes is much more dominant than others. Similar splitting has also been expected from edge roughness [12], and therefore other parameters that need to be considered in future for designing single mode resonant Nano cavities.

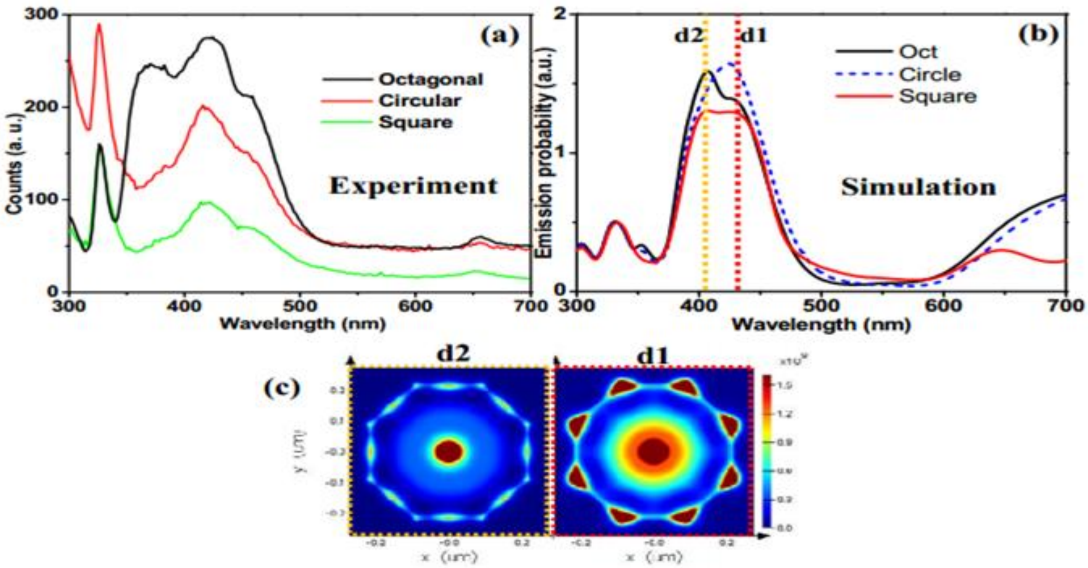

Figure 5: Spectra of the three disks with different geometries for excitation using electron-beam fixed at center. (a) Experimental measurements and (b) the corresponding simulations. Splitting of degeneracy is clearly captured in simulations as the disk "circularity" changes. (c) Electric field patterns for octagonal disk at the two peaks show different spatial field distribution with maxima at corners (d1) and edges (d2).

CONCLUSIONS

This paper discusses various aspects related to the study of optical Nano-antennas. Because of their Nano scale size, both fabrication and characterization of optical antennas offer significant challenges for harnessing their unique properties for a wide range of applications. Therefore, a broader approach involving patterning, characterization and applications is taken. This should enable future studies of optical antennas by providing fundamental understanding of their behavior as well as simple methods of manufacturing them.

This paper investigates the highly localized ultra-small modes of Nano-disks which are a new class of resonators with characteristic dimensions comparable to their resonance wavelengths. Their large sizes result in several modes that are spatially and spectrally resolved using localized excitations. As an example of how CL allows mapping of important

properties of the resonators, the effect of disk geometry on mode splitting was discussed.

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